RADARSAT Determination of the Outlines of the Successively Collapsing Caldera at the Miyakejima 2000 Eruption, Japan

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1. Introduction

Observing topographic changes at active volcanoes is one of the most basic but important elements for monitoring the status of an ongoing volcanic eruption. Suitably equipped aircraft, or Earth orbiting satellites such as SPOT or IKONOS, are able to provide optical imagery from which topographic detail can be extracted. However, as is well known, in humid climates such as Japan cloud cover can seriously impede the usefulness of data taken at these wavelengths. In 2000 an eruption at Miyakejima volcano (Japan) entailed the formation of a new caldera from successive collapse events, necessitating regular topographic surveys of the summit area. However thick clouds sometimes prevented useful observations of the summit from the specially commissioned aircraft or helicopter-based overflights (Nakada et al., 2001). This prompted us to investigate the use of spaceborne Synthetic Aperture Radar (SAR) for the observation of topographic changes caused by these collapse events.

Spaceborne SAR allows us to illuminate the Earth’s surface with active microwave radiation and to measure the amount of signal backscattered to the radar antenna. The active nature of the illumination, coupled with the long microwave wavelengths, allow views of the surface to be constructed during daytime and nighttime overpasses, regardless of weather conditions. For this reason the use of SAR imagery has been widely touted in volcano monitoring, however there exists a potentially large geometric distortion problem due to the interplay of the SAR viewing geometry and the severe topography often found on volcanic terrain (Iisaka, 1998). Brilliant success has been achieved when using groups of SAR images processed using differential SAR interferometry to provide information on wide-scale but often very small-magnitude ground displacements such as those relating to volcanic inflation and deflation events (Rosen et al., 1996; Lu et al., 1997). However, ash fall and changes in surface moisture and vegetation sometimes make it difficult to obtain coherent data from differential interferometric SAR processing and the technique is usually unable to provide data on the gross topographic changes found at volcanic summits (Stevens et al., in press).

Here we study the use of individual RADARSAT SAR images, rather than interferometrically processed products, to provide information on the changing caldera at Miyakejima volcano, Japan. The caldera was formed and enlarged during successive collapses and we compare interpretations of the caldera rim derived from the SAR data to those inferred from the available non-cloudy aerial photographs. The aim is to evaluate the usefulness of routinely processed, rapidly delivered SAR data of this type for observing gross topographic changes at active volcanoes.

2. Background

2-1. Miyakejima Volcano

Miyakejima is an active volcanic island in the Pacific Ocean consisting of a strato-volcanic edifice with a 9 km basal diameter and a maximum elevation of around 750 m. The volcanic island is situated 200 km south of Tokyo and has been active for more than ten thousand years, last erupting in 1940, 1963, 1983 and 2000 (Tsukui and Suzuki, 1998). In the 2000 activity, a sub-aqueous eruption was accompanied by a dyke intrusion on 27 of June, this...
being followed by successive collapses of the summit area involving large phreatic to magmato-phreatic explosions. At the end of August a new summit caldera was formed with a rim altitude concentrated in the 650–700 m zone. Subsequent collapses enlarged the rim diameter to its current maximum of 1.6 km (Nakada et al., 2001). At the same time eruption plumes containing a very large amount of SO$_2$ have been constantly released (20,000–50,000 ton/day) from vents in the new caldera (Japan Meteorological Agency and the Committee on Prediction for Volcano Eruptions, released 5 February 2001).

2–2. RADARSAT SAR Data

The RADARSAT satellite is a Canadian Earth observation system carrying a C-band (5.3 GHz, 5.7 cm) SAR instrument which can vary its imaging incident angle, swath width and spatial resolution (Raney, 1998). The systems pointing capability, coupled with the day-night, all-weather radar imaging allows frequent observation of the same location on Earth’s surface; every two days with 30 m × 30 m spatial resolution (standard mode) or every three days at 10 m × 10 m spatial resolution (fine mode).

The RADARSAT SAR system illuminates the surface by transmitting pulses of microwave radiation obliquely to the ground in a direction perpendicular to the satellite motion, with a viewing incident angle of between 20 and 60 degrees. The SAR antenna receives microwave signals backscattered from the ground surface, which because they are recorded sequentially with time lead to the effects of relief-displacement, foreshortening and topographic layover over sloping terrain, effects which are not present in data taken with optical sensors.

During the period of caldera formation and enlargement a number of sets of RADARSAT SAR data were taken of Miyakejima. Typically the data were down-linked to the receiving station at the Research and Information Center, Tokai University under a mutual corporation contract with NASDA and were processed to the level of 'path image plus'. For this study we selected 3 fine-mode images taken on 20 July, 6 August and 6 September 2000 from the western side of the volcano, all with an incident angle of 38 degrees (Fig.1).

3. Methods

In severe topography such as that found at Miyakejima, without recourse to a full geometric model of the surface imaging process, the geometric distortion

Fig. 1. RADARSAT images (a) 20 Jul. 2000, (b) 6 Aug. 2000 and (c) 6 Sept. 2000. Each view is 12.5 km across.
Fig. 2. Outlines of the caldera rim as inferred from (a) RADARSAT images (solid circles show GCPs used for matching) and (b) Aerial photos. GCPs '6', '8' and '9' in Fig. 2b were not used for warping the 6 Sept. image. The base map is adopted from a part of 1:25,000 topographic map “Miyakejima” by Geographical Survey Institute, Japan.

present in the SAR imagery can reduce the accuracy to which we can assign SAR image pixels to particular geographic coordinates. A simple method to counteract such distortion and thus allow the multi-temporal comparison of SAR images is via polynomial geometric warping of the SAR imagery using simple affine transformations. The transformation equations can be deduced via the location of image Ground Control Points (GCPs) (e.g., Schowengerdt, 1997).

When selecting GCP's in optical data coastlines are often favoured since they are easily recognised due to the high spectral contrast between water and the solid land surface at visible and near infrared wavelengths. A similarly high spectral contrast often exists between water and the land surface at C-band radar wavelengths due to the specularly reflecting water surface and the typically much greater backscatter present over the land. However the 600–700 m elevation difference between the island coastline and the caldera rim causes serious errors in spatial mis-registration when using coastline GCP's to warp the Miyakejima imagery via affine transformations. This is due to the foreshortening effect introduced by the variably sloping topography and, since one of the aims of our study was to attempt to obtain precise outlines of the Miyakejima caldera from the SAR data, we instead selected GCPs at approximately the same elevation as the caldera rim (i.e., greater than 600 m altitude). In this higher altitude area characteristic landforms were adopted as GCPs, for example fissure vents, bends or splits in mountain streams and local topographic high points. In addition to their location on the RADARSAT SAR imagery, the GCP coordinates were also identified on the vertical aerial photos, on images from a Japanese Airborne SAR system flown over the volcano (Communication Research Laboratory, Japan, http://www.cril.go.jp/) and on 1:10000 scale topographic maps. Figure 2a includes the GCP locations and by using these with an affine transformation the RADARSAT imagery were registered to a 1:25000 scale topographic map with an RMS (root mean square) error of 66, 53 and 48 m respectively for the 20 July, 6 August and 6 September 2000 datasets. Finally, manual interpretations of the caldera outline were determined from each geocoded SAR image and from the correspondingly geocoded aerial photographs.

4. Results

The resulting outlines of the caldera determined from the multi-date RADARSAT imagery are shown in Fig. 2a, making it obvious that the caldera enlarged its diameter with time. Collapses of the caldera occurred particularly in the southern and eastern areas, while being relatively small in the northern to eastern areas from 20 of July onward.
Figure 2b shows the matching caldera outlines determined from similarly dated aerial photographs (22 July and 2 August: Asia Air Survey, 18 September: Japan Air Self-Defence Force). The difference between the similarly dated SAR and photographic interpretations of the caldera outline is consistently less than one hundred meters.

A distinct example of topographic change easily observed via the RADARSAT SAR imagery is shown in Fig. 3. This figure shows the area around the Suo-ana crater, which was located on the retreating wall of the collapsing caldera. In this area the location of the caldera rims is easily recognised from the characteristic topographic and shape changes induced in the collapsing crater. From 20 July through 6 September 2000, the area of the Suo-ana crater can be seen to diminish by half.

5. Discussion and Conclusion

The main cause of the disagreement between the SAR and photographically determined caldera outlines shown in Fig. 2 is believed to be the 2–12 day difference in observation date and the relatively low number of available GCPs, which limits the accuracy of the applied affine transformations. However even if these conditions were improved two factors that cannot be corrected by our current simple but easily applied data processing method would remain, both being related to the foreshortening effect present in SAR imagery of sloping topography. One factor results from the differences in elevation amongst the GCPs, whilst the other is due to the systematic elevation difference between the selected GCPs and the caldera rim to be inferred. Though the GCPs were distributed near the caldera rim so as to minimise error due to this effect, the rim elevation is not constant but varies by up to around 100 m, causing small-scale geometric distortions in the geo-coded images. Mitigating the effects of these two factors would require us to adopt a more complex data processing method, something that may not be possible when required to produce rapid data for an emergency monitoring situation. However the acceptable differences seen here between the SAR and photographic interpretations of the caldera rim indicate that SAR imagery is sufficiently capable to be used for emergency topographic surveillance during volcano eruptions.

In next 10 years a number of new SAR equipped

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Fig. 3. Topographic changing around the Suo-ana crater. (a)–(c) RADARSAT images and (d) Topographic map of the same area (before eruption) (1 : 25,000 topographic map "Miyakejima" by Geographical Survey Institute, Japan).
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References


RADARSAT 画像による三宅島 2000 年陥没カルデラの地形解析

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噴火中の火山で、どのような地形変化が起きているかを知ることは、活動状況を把握するうえで、最も重要な点の一つである。しかし、我が国のような湿潤な気候帯では、しばしば、山頂部が雲に覆われ観測できない事態が起こる。このような場合、合成開口レーダー (SAR) は、昼や、天候、噴火等に左右されないため、火山の地形変化の監視に有効であると考えられる。しかし、SAR 画像は、独自の歪みをもつため、地形図との対応関係を知ることが容易できないなどの問題がある。本論文は、RADARSAT SAR 画像を Ground Control Points (GCP) を用いたマッチングにより地形図上に重ね合わせ、2000 年 7 月に噴火を開始した三宅島陥没カルデラ縁の拡大状況の推定を行った。この際フォアシートニングによる歪みを抑えるため、カルデラ縁に近い場所に GCP を設定した。得られた結果を空中写真等からの推定と比較すると、両者のずれは大きい部分でも 100 m 程度であり、比較的良好一致していることがわかった。このことから、RADARSAT SAR 画像は、緊急時にカルデラ縁の位置を推定するといった用途には十分利用できると考えられる。

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